Dynamic models of branching faults and surface rupture in the Signal Hill Stepover on the Newport-Inglewood Fault, Southern California

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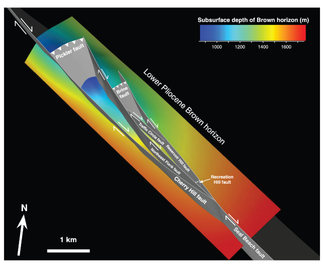
Abstract

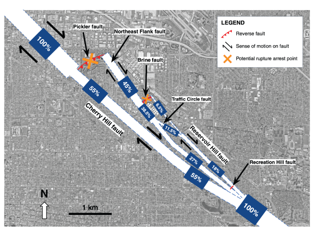
The right-lateral Newport-Inglewood Fault (NIF) system cuts across the highly populated Los Angeles (LA) metropolitan area. A segment of the fault sourced the highly destructive 1933 MW 6.4 Long Beach Earthquake, and the system poses significant seismic hazard to Southern California. Throughout the LA area the fault is highly segmented in its surface expression. At Long Beach, it manifests as a complex system of splay faults and linking reverse faults, leading to local uplift of Signal Hill and Reservoir Hill. Oil industry logs and other data sets help to precisely define the fault geometry in this area, while offset geological markers and topographic evidence help to determine the slip history across multiple splays of this fault system [Toghramadjian and Shaw, 2024].

To understand the past behavior and future earthquake potential of this region, we use the 3D discontinuous Galerkin method [Zhang et al., 2023] to model the dynamics of potential earthquakes on the NIF system in the Signal Hill region. Our main goal is to determine which factors determine the complex rupture paths implied by observational data. We are also exploring which factors may cause ruptures to terminate at the restraining bend system, as is thought to have occurred in the 1933 earthquake [Hough and Graves, 2020]. With homogeneous material properties, we find a strong directional dependence in the ability of earthquakes to propagate to the splay and reverse faults: earthquakes propagating from southeast to northwest can activate the splay faults, resulting in vertical uplift of the local hills, in agreement with observations. We note that slip on the Reservoir Hill fault tends to shadow and prevent slip on the Northeast Flank fault, suppressing uplift of Signal Hill. In contrast to the northwestward directed ruptures, earthquakes that propagate in the reverse direction from northwest to southeast approach the branches in the reverse direction, for which propagation to the splays corresponds to dynamically-inhibited backwards branching [e.g., Kame et al., 2003]. In such cases, there is essentially no slip on the splay faults, and no uplift of the hills in the region. Depth-dependent material properties, with higher wavespeeds at depth, greatly complicate the above picture, indicating the importance of 3D effects in determining rupture propagation at geometrical complexities. The results have implications for the surface rupture and ground motion hazard in this densely populated region, as well as for complex strike-slip/reverse-faulting systems worldwide.

Observational Evidence of Fault Structure and Rupture Propagation



Using geological maps and cross-sections, oil industry logs, seismic reflection data, and tomography studies, we are able to identify and constrain the geometry of a potentially significant earthquake gate in the Signal Hill region of the Newport-Inglewood fault in Los Angeles. It consists of multiple strike-slip strands connected by linking thrust faults, with uplift on the thrust faults producing Signal Hill and Reservoir Hill. The geometry merges into a more continuous structure at depths below ~4 km (Toghramadjian and Shaw, 2024).



The complex fault geometry inferred above provides a multitude of potential rupture paths through the Signal Hill region, each of which would produce different patterns of near-fault ground deformation, shaking, and damage. We use map-based restoration techniques to infer the cumulative slip through each of the fault segments, and thus how slip on average has been partitioned (Toghramadjian et al., 2024). The results above pose questions about the physical processes leading to the inferred rupture paths during individual events and over the long term.

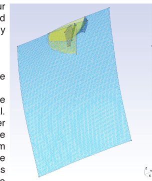
Research Questions

- Which factors (e.g., fault geometry, stress, frictional properties, seismic velocity structure) controls the dynamic branching process in this fault system?
- What is the directional dependence of rupture in this restraining bend?
- Which sets of parameters above best reproduce the variety of rupture behaviors inferred from the geologic observations?
- Under what conditions could the complex geometry result in rupture termination, as in the case of the 1933 Long Beach earthquake?

To address these questions, we utilize 3D spontaneous dynamic rupture modeling under a variety of assumptions about initial conditions.

Dynamic Faulting Model

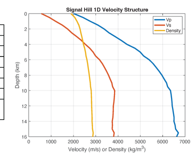
We use the 3D mixed-flux nodal discontinuous Galerkin method (Zhang et al., 2023) to perform our dynamic fault models, using a mixture of Cubit, Gmsh, and Rhino3D software to construct our mesh (figure on right). We implement all inferred fault segments with the exception of the extremely small Recreation Hill fault.



We utilize two different material structures:

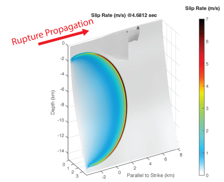
- A homogeneous model with properties in the table below
- A 1D velocity structure drawn from average values of the SCEC CVM 15.1.1 (Shaw et al. 2015) using the SCEC UCVM Explorer (doi.org/10.5281/zenodo.5651276) for the Signal Hill vicinity at depth intervals of 500 m (figure below to the right). Note that we assume each 500 m layer to have constant properties equal to those of the bottom point; thus we do not utilize the top very-low velocity layer.
- Stress is assigned via gravitational loading and pore fluid pressurization, with a fluid overpressure below 3 km depth providing a constant effective normal stress below 3 km.

Static Friction	0.5
Dynamic Friction	0.1
Slip Weakening	0.2 m
Homogeneous Density	2670 kg/m^3
Homogeneous V_P	6000 m/s
Homogeneous V_S	3464 m/s
Mesh Size on Faults	~100 m
Expanded mesh near edge of model	~5000 m

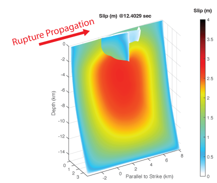


Large-Scale Rupture Propagation and Slip Across Entire Fault System

Homogeneous Velocity Model

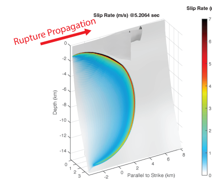


Homogeneous materials and a constant regional stress field below 3 km depth leads to roughly constant rupture propagation speeds across the fault and a roughly circular subshear rupture front.

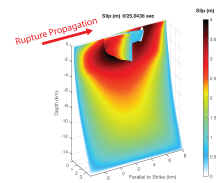


Constant effective normal stress below 3 km depth (due to the fluid overpressure) leads to roughly constant slip at depth in the fault system, with reduced slip near the surface due to the reduction in normal and shear stress at shallow depths. In this example, slip is partitioned primarily between the Reservoir Hill and Cherry Hill faults.

Heterogeneous Velocity Model



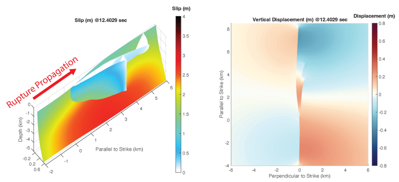
Faster wavespeeds at depth lead to faster rupture propagation at depth, and a slightly more upward-directed rupture propagation toward the near-surface fault branches. This small change in rupture front shape can have significant effects on the rupture path and final slip on the near-surface branches.



Slower wavespeeds near the surface lead to amplification of fault slip near the surface relative to the homogeneous model. In this example, slip is partitioned primarily between the Reservoir Hill and Cherry Hill faults.

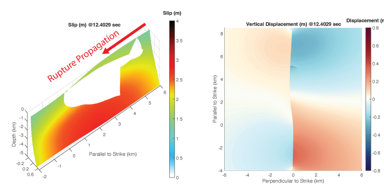
Focus on Branch Slip and Vertical Uplift

Homogeneous Velocity Model
SE to NW Rupture Propagation



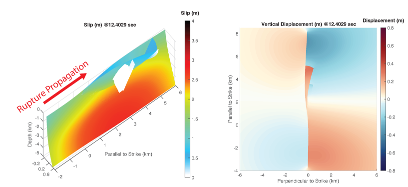
When propagating in the "forward branching" direction, rupture preferentially takes the first extensional branch it hits--the Reservoir Hill fault. This is one of the less observed rupture propagation pattens in the data. Uplift is produced in the Reservoir Hill region, but not Signal Hill.

Homogeneous Velocity Model
NW to SE Rupture Propagation



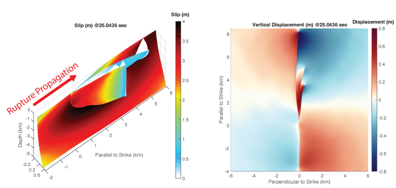
Rupture propagation in the "backwards branching" direction does not take any of the fault branches, similar to the 2D models of Kame et al. (2003). For the homogeneous velocity model, the rupture front approaches the branches in a largely mode-II manner, making the 2D rules for fault branching relatively applicable.

Homogeneous Velocity Model
SE to NW Rupture Propagation
Reservoir Hill Fault Constrained Not to Slip



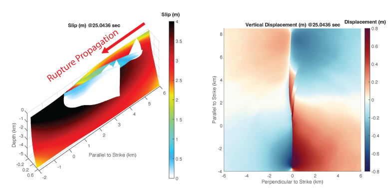
If the Reservoir Hill fault is artificially constrained not to slip (with a very high static friction coefficient), rupture instead takes the Northeast Flank fault, leading to slip on the Pickler fault and uplifting the Signal Hill area.

Heterogeneous Velocity Model
SE to NW Rupture Propagation



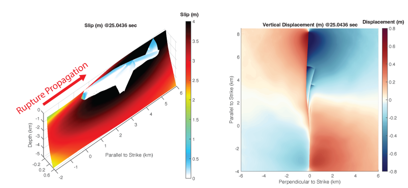
The 1D vertical velocity structure produces greater near-surface slip and ground deformation. For the "forward branching" rupture, relative partitioning of slip is similar to that of the homogeneous case, with preferential slip on the Reservoir Hill fault.

Heterogeneous Velocity Model
NW to SE Rupture Propagation



In contrast to the homogeneous case above, "backwards" rupture propagation in the 1D velocity case produces significant slip on the Northeast Flank fault. This result is likely due to the more upward-directed rupture propagation; the 2D approximation that underlies the concept of "backwards branching" no longer applies because the rupture is approaching the branches in more of a mode III direction from below.

Heterogeneous Velocity Model
SE to NW Rupture Propagation
Reservoir Hill Fault Constrained Not to Slip



In sharp contrast to the homogeneous case in the panel directly above, "forward" rupture propagation in the absence of the Reservoir Hill fault in the 1D velocity structure produces almost no slip on the fault branches. As in the "backwards" case in the panel to the left, this result is likely due to the more complex Mode-III and Mode-II stress transfer between the fault branches.

Discussion

- Branching behavior in models of the Signal Hill region of the Newport-Inglewood fault is strongly dependent on the direction of rupture propagation.
- Different assumptions of rupture propagation direction and material structure can produce some of the various rupture patterns inferred from observational data.
- Few models cause slip on the thrust faults in the region, and thus have some difficulty reproducing the uplift of Signal Hill, and to a smaller degree Reservoir Hill.
- Even though the fault geometry is strongly 3-dimensional, homogeneous-material models produce results that can be interpreted via simple 2D models of mode II branched faults, such as Kame et al. (2003).
- The incorporation of a 1D layered velocity structure causes a more strongly curved rupture front that interacts differently with the branched geometry, including approaching it more upward from below than along strike, and thus with a higher contribution of mode III. The effects of rupture curvature on the propagation of rupture, particularly at geometrical complexities, has been examined by Bazan Flores et al. (2024) and Abdelmaguid et al. (2024).
- In spite of dynamic stress shadowing, simultaneous rupture of multiple strands is possible.
- Current simulated ruptures do not terminate at the restraining bend.
- Future work will incorporate the full 3D heterogeneous materials of the region, including bimaterial interface effects, both of which may have a strong effect on the propagation of rupture and partitioning of slip.

References

Abdelmeguid, M., A. Elbanna, and A. Rosakis (2025), Ground motion characteristics of subshear and supershear ruptures in the presence of sediment layers, Geophysical Journal International, 240(2), 967-987.

Bazán Flores, L. I., C. Kyriakopoulos, D. D. Oglesby, A. J. Meltzner, T. K. Rockwell, J. M. Fletcher, and D. Brothers (2024), Exploring the dynamic interactions between the Southern San Andreas Fault and a normal fault under the Salton Sea, Journal of Geophysical Research: Solid Earth, 129(11), e2023JB028621.

Kame, N., J. R. Rice, and R. Dmowska (2003), Effects of pre-stress state and rupture velocity on dynamic fault branching, Journal of Geophysical Research, 108(B5), 2265, doi: 2210.1029/2002JB002189.

Shaw, J. H., A. Plesch, C. Tape, M. P. Suess, T. H. Jordan, G. Ely, et al. (2015), Unified structural representation of the southern California crust and upper mantle, Earth and Planetary Science Letters, 415, 1-15.

Toghramadjian, N., and J. H. Shaw (2024), 3D Geometry and Slip Distribution in the Long Beach Earthquake Gate, Newport–Inglewood Fault, Los Angeles, California, Bulletin of the Seismological Society of America, 114(4), 1941-1965.

Zhang, W., Y. Liu, and X. Chen (2023), A Mixed-Flux-Based Nodal Discontinuous Galerkin Method for 3D Dynamic Rupture Modeling, Journal of Geophysical Research: Solid Earth, 128(6), e2022JB025817.

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